Correlating Storm Surge Heights with Tropical Cyclone Winds at and before Landfall

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ABSTRACT: This paper investigates relationships between storm surge heights and tropical cyclone wind speeds at 3-h increments preceding landfall. A unique dataset containing hourly tropical cyclone position and wind speed is used in conjunction with a comprehensive storm surge dataset that provides maximum water levels for 189 surge events along the U.S. Gulf Coast from 1880 to 2011. A landfall/surge classification was developed for analyzing the relationship between surge magnitudes and prelandfall winds. Ten of the landfall/surge event types provided useable data, producing 117 wind–surge events that were incorporated into this study. Statistical analysis indicates that storm surge heights correlate better with prelandfall tropical cyclone winds than with wind speeds at landfall. Wind speeds 18 h before landfall correlated best with surge heights. Raising wind speeds to exponential powers produced the best wind–surge fit. Higher wind–surge correlations were found when testing a more recent sample of data that contained 63 wind–surge events since 1960. The highest correlation for these data was found when wind speeds 18 h before landfall were raised to a power of 2.2, which provided $R^2$ values that approached 0.70. The $R^2$ values at landfall for these same data were only 0.44. Such results will be useful to storm surge modelers, coastal

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scientists, and emergency management personnel, especially when tropical cyclones rapidly strengthen or weaken while approaching the coast.

**KEYWORDS:** Storm surge; Hurricanes; Tropical cyclones; Air–sea interaction

1. Introduction

Scientific literature on the physical processes that generate storm surge has developed substantially in recent years, as researchers investigate the role that complex variables such as bathymetry (Weisberg and Zheng 2006; Westerink et al. 2008; Chen et al. 2008) and tropical cyclone size (Blain et al. 1998; Irish et al. 2008; Dietrich et al. 2011) have on storm surge development. Such research has shown that these factors contribute to the height, extent, and timing of storm surge. However, one area that has not received much attention is the impact of prelandfall hurricane winds on storm surge at coastlines.

To date, only Jordan and Clayson (Jordan and Clayson 2008) have investigated this topic in any depth. They found that surge magnitudes correlate better with prelandfall winds than wind speeds at landfall, as they conducted a landfall/surge correlation analysis for 39 landfalling U.S. hurricanes from 1986 to 2007. They found that instantaneous wind speeds 12 h before landfall and scaled prelandfall intensity 24 h before landfall correlated best with surge heights.

Unfortunately, this important discovery has received little attention in the scientific literature. No other studies have investigated this topic in more depth or explained the physical processes responsible for this phenomenon, although it is thought that prelandfall winds correlate better with surge heights because of the oceanic response time required to transfer energy from the atmosphere to the water column (Jordan and Clayson 2008).

Several Gulf Coast hurricanes have rapidly strengthened or weakened just before landfall, providing a unique opportunity to better understand the relationship between prelandfall winds and peak surge heights. For example, Hurricane Lili in 2002 rapidly weakened just before landfall but generated a higher surge than might have been anticipated. Although Lili made landfall as a category 1 hurricane, with maximum sustained winds of 148 km h\(^{-1}\) (80 kt), the storm generated a 3.75-m surge in south Louisiana (Pasch et al. 2004). Strong prelandfall winds may explain how this hurricane generated such a large surge; while centered over the northcentral Gulf of Mexico, Lili was a category 4 hurricane with sustained winds of 232 km h\(^{-1}\) (125 kt) (Pasch et al. 2004).

Two years after Lili, Hurricane Charley provided an example of a rapidly intensifying storm that generated a relatively small storm surge. Although Charley made landfall in southwestern Florida as a category 4 hurricane, with maximum sustained winds of approximately 241 km h\(^{-1}\) (130 kt), the peak surge level observed in this storm was only 2.13 m at Sanibel and Estero Islands (Pasch et al. 2011). A storm tide at Fort Myers Beach was measured at 2.87 m above the National Geodetic Vertical Datum of 1929, but this observation was not adjusted for tides or datum (Wang et al. 2005). All of these observations were noticeably lower than the forecasted levels of 3.05–4.57 m provided by the National Hurricane Center (National Hurricane Center 2004) as Charley approached the coast. Weaker prelandfall winds may have contributed to this relatively small-magnitude surge.
Less than 8 h before landfall, while passing over the Dry Tortugas, Charley’s maximum sustained winds were 176 km h\(^{-1}\) (95 kt) (Pasch et al. 2011), 65 km h\(^{-1}\) (35 kt) slower than at landfall. Charley’s small size may have also contributed to the tempered surge levels (Franklin et al. 2006).

The next year, Hurricane Katrina struck coastal Louisiana and Mississippi, generating a storm surge that reached a peak elevation of 8.47 m at Pass Christian, Mississippi (Knabb et al. 2011). This was the highest surge level in modern U.S. history (Needham and Keim 2012). In addition to Katrina’s large size (Irish et al. 2008) and shallow bathymetry along the storm’s track (Chen et al. 2008), strong prelandfall winds likely also contributed to its massive storm surge. Katrina’s peak winds in the Gulf of Mexico reached as high as 278 km h\(^{-1}\) (150 kt) (Beven et al. 2008), placing the storm well over the minimum wind speed threshold of a category 5 hurricane. However, as Katrina approached the Louisiana and Mississippi coasts, the storm weakened, making final landfall as a category 3 hurricane with maximum sustained winds of 194 km h\(^{-1}\) (105 kt) (Knabb et al. 2011).

To better understand the role of wind timing in storm surge generation, this paper investigates the role of prelandfall winds as a predictor of storm surge height in more detail than previous research. We examine a storm surge dataset for the U.S. Gulf Coast that is substantially longer than the limited dataset employed by Jordan and Clayson (Jordan and Clayson 2008), thereby including a greater sample size of tropical storms and hurricanes. The two objectives are 1) to produce a landfall/surge classification system that characterizes the location of landfall relative to the peak storm surge for hurricanes that impacted the U.S. Gulf Coast and 2) to use this landfall classification to test the relationship between storm surge levels and wind speeds at 3-h increments preceding landfall for tropical cyclones along the U.S. Gulf Coast.

2. Data

Tropical cyclone position and wind intensity data are provided by Elsner and Jagger (Elsner and Jagger 2013). This dataset contains hourly information on tropical cyclone position, maximum winds, forward speed, and direction. The authors used spline interpolation to calculate nonlinear tropical cyclone data from 6-h observations provided by the Hurricane Database (HURDAT).

Storm surge data are provided by the Storm Surge Database (SURGEDAT), a storm surge database that provides surge data for the U.S. Gulf Coast from 1880 to 2011 (Needham and Keim 2012). As of February 2013, SURGEDAT has identified 189 surge events at least 1.22 m high along the U.S. Gulf Coast. SURGEDAT also provides envelopes of water for more than 150 U.S. surge events, supported by more than 7600 high-water marks (Needham et al. 2013). As better data have become available, some adjustments have been made to the peak surge height and/or location of maximum surge. An updated surge dataset is available online (at http://surge.srcc.lsu.edu).

Although Jordan and Clayson (Jordan and Clayson 2008) provided useful analysis on the wind–surge relationship, some notable differences exist between their dataset and the data used in our study. One difference is that they incorporated landfall events from both the U.S. Atlantic and U.S. Gulf Coast, while we only included tropical cyclones that impacted the U.S. Gulf Coast. Despite the larger
breadth of their study, they utilized a limited dataset of only 39 landfall events over a 22-yr period from 1986 to 2007. Also, their storm surge data came from only one source: the National Hurricane Center. In contrast, we utilize 189 surge events over a 130-yr period. In addition, SURGEDAT compiles surge data from at least 62 separate sources (Needham and Keim 2012), including 28 federal sources, numerous academic publications, and more than 3000 pages of historic newspaper, to provide a robust history of observed surge levels. As might be expected, in many cases, data from SURGEDAT differ considerably from surge levels utilized by Jordan and Clayson (Jordan and Clayson 2008). For example, Jordan and Clayson (Jordan and Clayson 2008) utilize a surge level of only 2.13 m for Hurricane Wilma’s surge in southwest Florida in 2005, although multiple credible sources provide surge estimates of at least 4.72 m (Barnes 2007; Smith et al. 2009).

Wind and surge data were analyzed for the period 1880–2011 (132 years), as well as a more recent, 52-yr analysis, covering the years 1960–2011. This more recent time period is selected to validate the longer analysis. A start date of 1960 for the more recent analysis enables inclusion of the entire era of tropical satellite meteorology, which began operationally in the early 1960s (Fett 1964; Timchalk et al. 1965; Dvorak 1984). Improved hurricane tracking and intensity data from the satellite era should provide more accurate analysis related to the correlation of hurricane winds and surge heights. Also, several high-profile hurricanes struck the Gulf Coast in the 1960s, including Hurricanes Donna, Carla, Betsy, Beulah, and Camille.

3. Methods

As this paper correlates tropical cyclone winds and storm surge heights at landfall and at 3-h prelandfall increments, determining the precise time and location of landfall is crucial. Although the National Hurricane Center defines the term landfall to be “the intersection of the surface center of a tropical cyclone with a coastline” (National Hurricane Center 2012a), determining the exact time and location of a hurricane landfall is sometimes ambiguous.

Hurricanes that move very slowly or remain stationary near the coast provide cases in which the time and location of landfall may be unclear. This may be especially true if the coastal zone contains wetlands, marshes, or estuaries, as these features make it difficult to determine the boundary between land and sea. Hurricane Isaac in 2012 provides such an example, as the storm remained stationary near the southeast Louisiana coast for a period of time between its first and second landfall (National Hurricane Center 2012b). As this portion of coastline contains many wetlands and small islands, it is possible that Isaac technically made more than two landfalls.

Tropical cyclones that make several distinct landfalls make it difficult to determine which landfall relates best in time and space to the peak storm surge event. Such storms may loop as they approach the coast or may briefly track over peninsulas or other protrusions of land before reemerging over water and making another landfall. For example, in 1985, Hurricane Juan made a series of loops that impacted south Louisiana (Case 1986). The storm made an initial loop off the Louisiana coast, before the first landfall. After this landfall, the storm moved inland and made a second loop around Lafayette, Louisiana, before reemerging into the

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Gulf of Mexico as a tropical storm and moving to the northeast, making a second Louisiana landfall in Plaquemines Parish (Unisys 2012). The system then continued moving northeastward, making its final landfall along the Alabama coast (Unisys 2012).

SURGEDAT contains 12 storm surge observations from Hurricane Juan: the highest of which is 2.5 m at Bayou Bienvenue, Louisiana, near New Orleans. However, given the erratic nature of Juan’s track, it is difficult to know which landfall associates closest with the peak storm surge level.

Other hurricanes make only one distinctive landfall; however, the time and location of the landfall are separated in time and space from the peak storm surge. This is especially likely to occur if the hurricane tracked near the coastline for several hours before making landfall. Hurricane Andrew’s Louisiana landfall fits into this category. Andrew approached the Louisiana coast as a category 4 hurricane. At 0300 UTC 26 August 1992, Andrew was centered near 28.84°N, 90.92°W, about 52 km [28 nautical miles (n mi)] southwest of the location of peak storm surge. The maximum sustained winds at this time were 233 km h\(^{-1}\) (126 kt) (Elsner and Jagger 2013). As the radius of maximum winds was 28 km (15 n mi), Andrew’s eyewall made a direct hit on the location of peak surge, because the distance from the center of the eye to the location of peak surge was less than double the radius of maximum winds (National Hurricane Center 2012a). However, the center of circulation remained offshore for more than 5 h after this closest approach to the location of peak surge. When the center of circulation finally crossed the coast, after 0800 UTC, the maximum sustained winds had dropped to 202 km h\(^{-1}\) (109 kt) and the distance from the center of circulation to the location of peak storm surge had increased to 94 km (51 n mi). As such, Andrew’s position and intensity related better to the location of peak storm surge when it was passing just off the coast from this location than when the storm officially made landfall. It should be noted that the location of peak storm surge was accurately observed and not influenced by a scarcity of storm surge data. SURGEDAT provides 74 high-water marks in this region from Hurricane Andrew, where many of which are closer to the official landfall location than the peak surge location (Figure 1).

These examples introduce problems with using the standard landfall definition to study the correlation between storm surge magnitudes and hurricane winds at landfall and incremental time periods approaching landfall. Therefore, we developed a unique classification system that categorizes storm surge events into one of 14 landfall/surge categories. The spatial relationship between hourly hurricane positions and the location of peak storm surge determine the class identification.

We utilized the R Program for Statistical Computing software (R Development Core Team 2011) to plot the location of peak storm surge and hourly tropical cyclone locations. A minimum distance function was then incorporated to determine the closest hourly storm observation to the location of peak storm surge. For many cases, we classified this closest hourly observation (CHO) as the time of landfall. However, in some cases, CHO occurs after the tropical cyclone has crossed land. This introduces problems to the classification of landfall, particularly if the cyclone has been inland for at least several hours before CHO is classified. As such, we visually determined the closest offshore observation (COO) as the offshore observation closest in time to CHO and considered COO to be the time of landfall for cases in which CHO occurred inland.
This methodology produced 14 types of landfall/surge events based upon the timing of CHO and COO, as well as the movement of the tropical cyclone and the spatial comparison between the location of peak storm surge and hourly tropical cyclone locations. Table 1 provides a list of these event types, the number of events for each type, and an example tropical cyclone for each type. Of the 14 types, 10 were included in the statistical analysis (types 1–10), which comprised 117 landfall/surge events. Four types (types 11–14) were not included in this analysis, removing 72 landfall/surge events. Types 1–4 represent events in which CHO occurs offshore, whereas types 5–9 are events in which CHO occurred inland. Types 10–14 represent a variety of different landfall/surge scenarios, which were removed from this analysis because of dissociation of the wind–surge relationship in space and/or time, as described below.

3.1. Landfall/surge classification system

In type 1 events, CHO is the last hourly observation before a tropical cyclone crosses the coastline. The timing of CHO is coordinated very well with the official landfall time in these events, producing a pattern that is generally considered to be a typical landfall. Hurricane Bonnie in 1986 (Figure 2a) is an example of this type, as CHO equals COO and occurs as the last hourly observation before the storm crosses the southeast Texas coast. Bonnie generated a peak storm surge at Sabine Pass, Texas, a location just east of landfall.
In type 2 events, CHO occurs two or three observations before the tropical cyclone actually crosses the coast. In these cases CHO is also equal to COO. Hurricane Lili in 2002 (Figure 2b) is an example of a type 2 event, as CHO occurred almost 2 h before the center of Lili’s circulation actually crossed the Louisiana coast.

In type 3 events, CHO occurs more than 3 h before the center of circulation crosses the coast. In these cases, CHO is equal to COO. Hurricane Andrew in 1992 (Figure 2c) is an example of a type 3 event, as CHO occurred more than 5 h before the center of Andrew’s circulation crossed the Louisiana coast.

Type 4 events have multiple landfalls. In these cases, CHO is also an offshore observation, but this occurs after the tropical cyclone has previously made landfall. As such, in type 4 events, CHO is equal to COO and occurs as the last offshore observation before the second landfall. Hurricane Jerry in 1989 (Figure 2d) is the example of this type, as the hurricane made landfall near Galveston Island and then briefly tracked inland west of Texas City, Texas, before emerging into Galveston Bay and generating a peak storm surge at Baytown, Texas.

Type 5 events typify cases in which the CHO is the first inland observation. In these events, CHO = COO + 1 and the first observation before CHO is selected as the landfall observation. Hurricane Opal in 1995 (Figure 2e) is an example of this type. It should be noted that, for cases in which CHO occurs inland, we always use COO as the landfall observation, so we are never using an inland observation to designate landfall.

Type 6 events are similar to type 5; however, CHO is the second inland observation. In these events, CHO = COO + 2 and the second observation before CHO is selected as the landfall observation. An unnamed hurricane in 1941 (Figure 2f), which made landfall near Apalachicola, Florida, is an example of a type 6 storm.

Type 7 events are similar to types 5 and 6; however, CHO is the third inland observation. In these events, CHO = COO + 3 and the third observation before CHO is selected as the landfall observation. Hurricane Edith in 1971 (Figure 2g) is an example of a type 7 event.

**Table 1. Frequency of the 14 landfall classes with a determination of inclusion/exclusion in this study.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description of the CHO</th>
<th>No. of events</th>
<th>Included or excluded</th>
<th>Example storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Last obs over water</td>
<td>25</td>
<td>Included</td>
<td>Bonnie</td>
</tr>
<tr>
<td>2</td>
<td>Obs over water: second or third obs before crossing land</td>
<td>19</td>
<td>Included</td>
<td>Lili</td>
</tr>
<tr>
<td>3</td>
<td>Obs over water: more than three obs offshore</td>
<td>16</td>
<td>Included</td>
<td>Andrew</td>
</tr>
<tr>
<td>4</td>
<td>Second landfall: last obs over water</td>
<td>1</td>
<td>Included</td>
<td>Jerry</td>
</tr>
<tr>
<td>5</td>
<td>First inland obs</td>
<td>27</td>
<td>Included</td>
<td>Opal</td>
</tr>
<tr>
<td>6</td>
<td>Second inland obs</td>
<td>7</td>
<td>Included</td>
<td>Unnamed</td>
</tr>
<tr>
<td>7</td>
<td>Third inland obs</td>
<td>6</td>
<td>Included</td>
<td>Edith</td>
</tr>
<tr>
<td>8</td>
<td>Second landfall: first inland obs</td>
<td>2</td>
<td>Included</td>
<td>Katrina</td>
</tr>
<tr>
<td>9</td>
<td>Second landfall: second inland obs</td>
<td>1</td>
<td>Included</td>
<td>Allison</td>
</tr>
<tr>
<td>10</td>
<td>Florida Keys surge event</td>
<td>13</td>
<td>Included</td>
<td>Donna</td>
</tr>
<tr>
<td>11</td>
<td>Landfall: four or more obs inland</td>
<td>22</td>
<td>Excluded</td>
<td>Matthew</td>
</tr>
<tr>
<td>12</td>
<td>Peak surge to left of landfall</td>
<td>17</td>
<td>Excluded</td>
<td>Unnamed</td>
</tr>
<tr>
<td>13</td>
<td>Peak surge and landfall locations far</td>
<td>24</td>
<td>Excluded</td>
<td>Gilbert</td>
</tr>
<tr>
<td>14</td>
<td>Tropical cyclone moving offshore</td>
<td>9</td>
<td>Excluded</td>
<td>Unnamed</td>
</tr>
</tbody>
</table>
In type 8 events CHO is the first inland observation of the second landfall. Although only two events are classified in this type, these events are extremely important. Hurricanes Camille and Katrina (Figure 2h) were both type 8 events. These tropical cyclones produced the two highest storm surges in the past
130 years along the U.S. Gulf Coast (Needham and Keim 2012). Both of these hurricanes traversed open water of the Gulf of Mexico before making landfall along the Louisiana Delta. These storms then both reemerged over water near Mississippi Sound and made a second landfall near the Louisiana–Mississippi border. In both cases, CHO is the first inland observation on the Louisiana or Mississippi mainland. Therefore, \( \text{CHO} - \text{COO} = 1 \) and the last observation before CHO is utilized as landfall.

Interestingly, Hurricane Camille’s COO actually occurs over land, as the last observation before final landfall occurred while it was still over the Louisiana Delta. However, it is necessary to use this observation as landfall, as the storm emerged over the Mississippi Sound and then made landfall again on the Mississippi mainland by the next hourly observation. This is a rare case where COO occurs over land; however, we feel it is representative of the storm intensity as it emerged into Mississippi Sound. Hurricane Katrina was centered over Lake Borgne at COO, 1 h before CHO, which occurred near Slidell, Louisiana.

Type 9 events are similar to type 8 events, although CHO represents the second inland observation of the second landfall. In these cases \( \text{CHO} - \text{COO} = 2 \), so the second observation before CHO is used as the landfall observation. Tropical Storm Allison in 1995 (Figure 2i) is classified as a type 9 event, as the storm briefly crossed Alligator Point, Florida, before reentering water and making a final landfall on the north shore of Apalachee Bay. Landfall in this case was defined as the second hourly observation before CHO.

In type 10 events, the peak storm surge occurred in the Florida Keys. These events were separated from surges that peaked on the mainland U.S. coast or on barrier islands located just off the U.S. mainland. This decision was justified by the fact that landfall is difficult to define in island chains like the Florida Keys, as the center of circulation for many tropical cyclones crosses between islands, crosses the edges of islands, or may traverse many different islands. Hurricane Donna in 1960 (Figure 2j) is classified as a type 10 event.

In type 11 events, CHO is classified as at least the fourth inland observation. Such events are not included in this analysis because the tropical cyclone makes its closest approach to the location of peak surge well after COO. It is reasonable to assume that the time of peak surge for many of these events occurred as the tropical cyclone passed closest to the location of peak surge. If the time of peak surge and COO are separated by 4 h or more, the tropical cyclone conditions when the center of circulation actually crossed the coast are likely to be different than the tropical cyclone conditions 4 h or more later.

The tropical cyclone in many of these cases makes landfall at an oblique angle to the coast, remaining near the coast for many hours after landfall. In other cases, the maximum surge occurs on the innermost portion of large bays or lakes, enabling the cyclone to continue approaching the location of peak storm surge many hours after it has already made landfall. Tropical Storm Matthew in 2004 (Figure 2k) provides such an example, as the storm made landfall in south Louisiana, near Cocodrie, Louisiana, and then continued to approach Frenier, the location of peak storm surge, for the next 5 h. Matthew’s center of circulation was inland during these 5 h but was still able to approach Frenier, as this small village is located near the westernmost portion of Lake Pontchartrain.
Type 12 events represent cases in which the location of peak storm surge was located to the left of the tropical cyclone track as the storm approached the coastline. In the Northern Hemisphere, storm surges generally peak to the right of the cyclone track, as these areas observe strong onshore winds from the counterclockwise wind flow around the cyclone. An unnamed hurricane that made landfall in the western Florida Panhandle in 1916 (Figure 2l) provides an example of this type of event. SURGEDAT provides a maximum surge height of 1.22 m in Mobile, Alabama, for this event; however, a higher storm surge may have occurred in the western Florida Panhandle, though no credible source of information is available.

In type 13 events, the location of peak storm surge and the CHO are far enough apart that the timing of peak storm surge is not likely associated with the timing of landfall. An example of such events includes tropical cyclones that generated storm surges in the United States but made landfall far enough south of the Texas–Mexico border that the eyewall never directly impacted the United States. This type also includes tropical cyclones that pass far enough south of the Florida Keys that the eyewall never crosses any islands and tropical cyclones that are in proximity to the coast, although they parallel the coast in such a way that the peak surge is separated in space and time from landfall. Hurricane Gilbert in 1988 (Figure 2m), for example, made landfall in Mexico, more than 200 km (108 n mi) south of the U.S. border, but still generated a storm surge of 1.83 m at South Padre Island, Texas (National Hurricane Center 1988). However, this surge height cannot be used in this analysis, because storm surge heights in Mexico were most likely larger than those in south Texas, estimated up to 3.96 m north of the landfall location (National Hurricane Center 1988).

We required COO to be located within 159 km (86 n mi) of the location of peak surge, effectively removing all events in which the tropical cyclone was too distant from the peak surge to associate the timing of landfall and peak surge. The size of this buffer corresponds to the average extent of tropical storm–force winds in category 1 and 2 hurricanes (Keim et al. 2007), which comprise most of the events in this analysis. An exception to this rule was made for Hurricane Emily, which was included as a type 13 event, even though the distance from COO to the location of peak surge was only 143.5 km (77.5 n mi). As Emily was a small storm, with a 28-km (15 n mi) radius of maximum winds (Demuth et al. 2006), and the storm made landfall well south of the Texas–Mexico border, it is likely that surge levels in Mexico exceeded the 1.52-m surge measured at Boca Chica Beach, in south Texas.

Tropical cyclones that generated storm surges while moving offshore are classified as type 14. These events are not included in the analysis because they are not making landfall in the Gulf of Mexico. Many of these events made landfall on the eastern coast of Florida and then emerged into the Gulf after traversing the peninsula. An unnamed hurricane in 1947 (Figure 2n) is an example of this type. This storm produced a 1.68-m surge in Everglades City as it emerged into the Gulf of Mexico after passing over south Florida.

3.2. Building a 3-h incremental wind speed dataset

The maximum wind speed for each storm was recorded in a database, beginning at 36 h before landfall and continuing at 3-h increments until the time of landfall. In
some cases, however, data were intentionally removed from one or more of the 3-h prelandfall increments.

One reason this occurs is that some storms developed into tropical storms less than 36 h before making landfall. In these cases, observations are not included in the database until the system forms into a tropical storm. Hurricane Humberto (Figure 3) provides an example of this phenomenon, as this storm only formed into a tropical storm 24 h before the time of COO. For this reason, wind data are removed for 27, 30, 33, and 36 h before landfall.

Another reason data may be missing from one or more of the 3-h observations is that a tropical cyclone was not centered over the Gulf of Mexico at the time of the observation. If the cyclone was centered over land, such as Florida or Cuba, or centered over water outside the Gulf of Mexico, such as the Atlantic Ocean or Caribbean Sea, observations were not included. For example, no observations are provided for Hurricane Charley from 15 to 36 h preceding landfall in southwest Florida, as the hurricane was centered over the Caribbean Sea, south of Cuba, during these intervals (Figure 4). An exception was made for tropical cyclones centered over the Atlantic Ocean if the cyclone was moving toward a peak storm surge location in the Florida Keys.

4. Results

4.1. LOESS and linear regression models

Analysis run on 117 tropical cyclones, from 1880 to 2011, reveals that prelandfall wind speeds correlate better with surge magnitudes than wind speeds at landfall (Table 2). Local regression (LOESS) modeling methods, which use localized regression analysis to find the optimal fit for nonlinear relationships, find that the
correlation between wind speeds and surge magnitudes from 3 to 30 h before landfall fit better than wind speeds at landfall. For the wind–surge relationship at each time increment, we calculated the residual standard error (RSE), which is sometimes called residual standard deviation (National Institute of Standards and Technology 2013) or standard error of estimate (Spiegel 1961). Lower RSE values indicate a better fit (National Institute of Standards and Technology 2013). We found the optimal wind–surge correlation occurs 18 h before landfall, when RSE values drop to 0.897. The RSE values at landfall were 1.109.

Also, the wind and surge observations 18 h before landfall clearly fit tighter to a LOESS regression line and have fewer outliers than wind speeds at landfall (Figures 5a,b). The observations for Hurricane Katrina fit well into this pattern, as

Table 2. Residual standard error between surge heights and wind speeds at landfall and 18 h before landfall. Lower values indicate better correlation.

<table>
<thead>
<tr>
<th>Hours before landfall</th>
<th>No. of observations</th>
<th>RSE 1880–2011</th>
<th>RSE 1960–2011</th>
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<tr>
<td>0</td>
<td>117</td>
<td>63</td>
<td>1.109</td>
</tr>
<tr>
<td>3</td>
<td>117</td>
<td>63</td>
<td>1.03</td>
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<td>6</td>
<td>117</td>
<td>63</td>
<td>0.9866</td>
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<td>117</td>
<td>63</td>
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<td>113</td>
<td>60</td>
<td>0.92</td>
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<td>109</td>
<td>59</td>
<td>0.897</td>
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</tbody>
</table>
the higher wind speeds 18 h before landfall shift this observation to the right in the
graphic, making it fit much better with the regression model.

Interestingly, a linear regression model does not fit the data as well as the LOESS
model. RSE values for the linear model at 18 h before landfall only fell to 0.9431.
This outcome supports the notion that wind and surge relationships are nonlinear,
as the RSE value from the LOESS method was lower (more optimal) than that of
the linear regression. The relationship between maximum sustained winds and
storm surge heights for both the LOESS and linear regression models are signifi-
cant at the 99% confidence level.

Analysis of more recent landfall/surge events revealed similar results. LOESS
regression modeling of wind and surge from 63 tropical cyclones between 1960
and 2011 revealed the lowest RSE values at 18 h before landfall as well, while
values from 3 to 30 h before landfall were lower than values at landfall. RSE values
at 18 h before landfall are 0.8579, which indicates a more optimal fit than on the
1880–2011 data. Interestingly, RSE values at landfall are 1.187, which is less
optimal than the 1880–2011 values (Figure 6). The RSE values for linear regres-
sion in the more recent data are also higher (less optimal) than nonlinear regression
modeling. The RSE values for the linear regression at 18 h before landfall are
0.9398. All values are significant at the 99% confidence level.

Multiple $R^2$ correlation tests find similar results. Correlations improve at each
3-h interval before landfall until reaching an optimal correlation 18 h before
landfall and then begin to drop off as the time before landfall exceeds 18 h. The $R^2$
values peaked at 0.6012 for data from 1880 to 2011 and 0.663 for data from 1960 to
2011. These correlations are noticeably better than correlations at landfall, which
were only 0.4299 for the longer dataset and 0.4369 for the most recent data.
Although multiple $R^2$ values at 18 h before landfall are noticeably higher than $R^2$
values at landfall, the confidence interval function in R, CI.Rsq(), indicated that
overlap exists in the 95% confidence level error bounds for these correlations,
using both the shorter and longer datasets. This means these $R^2$ values are not significantly different within their entire error bounds.

Table 3 and Figure 7a provide comparisons of $R^2$ values at 3-h intervals leading up to landfall for both of these time periods. Interestingly, as time before landfall increases, the difference in correlation values between the older and newer datasets increases, presumably because offshore tropical cyclone data have improved substantially during the era of satellite meteorology. These improved correlations between surge heights and prelandfall winds in the newer dataset result in every 3-h interval having better correlations than the correlation between surge and wind speeds at landfall.

4.2. Nonlinear wind–surge relationship

The RSE LOESS and linear regression models show that the relationship between maximum wind speeds and storm surge magnitudes is nonlinear. We investigated this topic in more depth by raising the array of wind speeds at each 3-h interval to various exponential powers and then finding which power produced the best fit on a linear regression.

Surprisingly, raising wind arrays to an exponential power greater than two produces the highest $R^2$ values. Optimal fitting occurs when wind speeds 18 h before landfall are raised to an exponential value of 2.2. When conducted on data from 1960 to 2011, raising wind speeds to an exponent of 2.2 increased multiple $R^2$ values from 0.6630 to 0.6948. Surge heights fit best with wind speeds 12 and 15 h
before landfall when these wind values were raised to a power of 2.4. Table 4 provides a list of $R^2$ values correlating surge heights to actual winds and winds raised to exponential powers for each 3-h interval for the 1960–2011 dataset, which are graphed in Figure 7b.

Although raising wind speeds to exponential powers maximizes the difference between multiple $R^2$ values at landfall and 18 h before landfall, the confidence

<table>
<thead>
<tr>
<th>Hours before landfall</th>
<th>1880–2011 (117 events)</th>
<th>1960–2011 (63 events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.4299</td>
<td>0.4369</td>
</tr>
<tr>
<td>3</td>
<td>0.5086</td>
<td>0.5341</td>
</tr>
<tr>
<td>6</td>
<td>0.5433</td>
<td>0.5793</td>
</tr>
<tr>
<td>9</td>
<td>0.557</td>
<td>0.6004</td>
</tr>
<tr>
<td>12</td>
<td>0.5693</td>
<td>0.6138</td>
</tr>
<tr>
<td>15</td>
<td>0.5717</td>
<td>0.6379</td>
</tr>
<tr>
<td>18</td>
<td>0.6012</td>
<td>0.663</td>
</tr>
<tr>
<td>21</td>
<td>0.5868</td>
<td>0.6473</td>
</tr>
<tr>
<td>24</td>
<td>0.5508</td>
<td>0.6124</td>
</tr>
<tr>
<td>27</td>
<td>0.5162</td>
<td>0.5657</td>
</tr>
<tr>
<td>30</td>
<td>0.4832</td>
<td>0.5408</td>
</tr>
<tr>
<td>33</td>
<td>0.4317</td>
<td>0.4932</td>
</tr>
<tr>
<td>36</td>
<td>0.3964</td>
<td>0.4698</td>
</tr>
</tbody>
</table>

Figure 7. (a) Correlation of surge height vs wind speeds at 3-h intervals for data from 1880 to 2011 (117 events) and from 1960–2011 (63 events). (b) Correlation of surge heights vs actual and exponential wind speeds at 3-h intervals for data from 1960 to 2011.
interval function in R once again indicates overlap in the error bounds for the 95% confidence level. However, this overlap does not exist for the 90% confidence level, in which the bounds for $R^2$ values at landfall range from 0.2935 to 0.5849 and the bounds for $R^2$ values 18 h before landfall range from 0.5921 to 0.7975. This test shows a statistically significant difference in the $R^2$ values of these datasets at the 90% confidence level, when tropical cyclone wind speeds are raised to exponential powers.

These results may seem improbable because wind force is proportional to the square of the maximum wind speed. It may appear that optimal fitting would occur when the wind array is squared; however, when we consider that the transfer of energy from air to water is not perfectly efficient, it seems reasonable that the optimal exponent should be less than 2 (Jordan and Clayson 2008). So how is it possible that an exponent greater than 2 produces the best fit?

One possible explanation for this result is the inverse barometer effect. Because surge levels rise in a dome as air pressure near the eye of the hurricane becomes lower, wind stress is not the only physical parameter forcing storm surge. Increased surface roughness provides another possible explanation. As winds increase, wave heights increase as well, increasing the surface roughness of the water. This may increase friction between air and water, making it more efficient for the wind to move more water, thereby increasing the surge height. Other physical parameters may include the geometry of the coastline and bathymetry of water near the coast, which may amplify the buildup of water that is already displaced by the wind. Another possible explanation is that hurricanes displace water over a period of time, which may enhance the buildup of water along the coast from hurricanes that have stronger prelandfall winds. Water displaced while the hurricane is approaching landfall will accumulate at the coast over time because of the geostrophic effect, and it makes sense that more water would accumulate if prelandfall winds were higher. By contrast, prelandfall winds should not directly cause wind damage at the coast because they are blowing over water and not directly impacting structures on the coast. All of these potential reasons for the nonlinear relationship between prelandfall winds and surge magnitudes are speculative and should be investigated by scientists.

### Table 4. Multiple $R^2$ values of surge vs actual and exponential wind speeds for data from 1960 to 2011 (63 events). The exponential power that produced optimal fit is also listed.

<table>
<thead>
<tr>
<th>Hours before landfall</th>
<th>$R^2$ of surge vs actual winds</th>
<th>$R^2$ of surge vs exponential winds</th>
<th>Optimal exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.4369</td>
<td>0.4392</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>0.5341</td>
<td>0.543</td>
<td>1.74</td>
</tr>
<tr>
<td>6</td>
<td>0.5793</td>
<td>0.5968</td>
<td>1.88</td>
</tr>
<tr>
<td>9</td>
<td>0.6004</td>
<td>0.6287</td>
<td>2.17</td>
</tr>
<tr>
<td>12</td>
<td>0.6138</td>
<td>0.6507</td>
<td>2.4</td>
</tr>
<tr>
<td>15</td>
<td>0.6379</td>
<td>0.6745</td>
<td>2.4</td>
</tr>
<tr>
<td>18</td>
<td>0.663</td>
<td>0.6948</td>
<td>2.2</td>
</tr>
<tr>
<td>21</td>
<td>0.6473</td>
<td>0.6671</td>
<td>1.92</td>
</tr>
<tr>
<td>24</td>
<td>0.6124</td>
<td>0.6244</td>
<td>1.65</td>
</tr>
<tr>
<td>27</td>
<td>0.5657</td>
<td>0.5729</td>
<td>1.53</td>
</tr>
<tr>
<td>30</td>
<td>0.5408</td>
<td>0.5497</td>
<td>1.62</td>
</tr>
<tr>
<td>33</td>
<td>0.4932</td>
<td>0.4954</td>
<td>1.32</td>
</tr>
<tr>
<td>36</td>
<td>0.4698</td>
<td>0.4703</td>
<td>1.15</td>
</tr>
</tbody>
</table>
in the geophysical research community who specialize in atmospheric and oceanographic physics.

These findings are important because they reveal that changes in prelandfall hurricane wind speed may impact surge height greater than previously expected. This may be especially important for the most intense tropical cyclones, which may displace more water than previously realized. For example, doubling the maximum wind speed increases the wind force by a factor of 4 but increases the surge potential by a factor of 4.59.

5. Discussion

These results are timely as the scientific community is reevaluating the tropical cyclone parameters that are most influential on storm surge generation. For decades, the National Hurricane Center associated wind categories on the Saffir–Simpson scale with potential storm surge heights, assuming higher category hurricanes will typically generate larger storm surges. This association was discontinued after Hurricane Ike made landfall as a category 2 hurricane but generated a massive 5.33-m surge along the Texas coast in 2008 (Berg 2010). At the time, the Saffir–Simpson scale generalized category 2 hurricanes as having the potential to generate a surge of 1.8–2.4 m (Irish et al. 2008). Ike’s surge occurred approximately three years after Hurricane Katrina made landfall as a category 3 hurricane but generated the largest storm surge in modern U.S. history (Needham and Keim 2012). Katrina’s surge of 8.47 m (Knabb et al. 2011) was noticeably larger than the 7.5-m surge generated by Hurricane Camille in 1969 (Simpson et al. 1970), which made landfall as a category 5 hurricane in the same region.

Hurricanes Katrina and Ike revealed the importance of hurricane size on storm surge generation, as the size of these storms likely contributed to their large surge magnitudes (Irish et al. 2008; Berg 2010). While centered over the northern Gulf of Mexico, Katrina was a large and powerful hurricane. At 18 h before landfall in Mississippi, the radius of 93 km h⁻¹ (50 kt) winds extended 222 km (120 n mi) and the radius of 119 km h⁻¹ (64 kt) winds extended 167 km (90 n mi) from the center of circulation, while maximum sustained winds were around 269 km h⁻¹ (145 kt) (Demuth et al. 2006). Hurricane Ike’s size was even more impressive, when it traversed the Gulf of Mexico in 2008. The radius of 93 km h⁻¹ (50 kt) winds was 278 km (150 n mi) and the radius of 119 km h⁻¹ (64 kt) winds was 194 km (105 n mi) approximately 18 h before landfall on the northern end of Galveston Island (Demuth et al. 2006).

Some may argue that Katrina and Ike revealed that hurricane size and bathymetry are the most important parameters for storm surge generation, as these large storms generated high-magnitude surges in areas with shallow bathymetry. Such conclusions may leave readers skeptical of our results, as it may appear that wind speeds do not correlate well with surge magnitudes.

To validate our results, we further investigated the characteristics of some tropical cyclones that generated surge events near each other in space. Analyzing surge events that were proximal to each other limits the influence of bathymetry, enabling the roles of hurricane size and wind speeds to be more visible. We compared Hurricanes Danny and Lili, which impacted south-central Louisiana in 1985 and 2002; the 1900 Galveston hurricane and Hurricane Ike, which impacted
the Houston–Galveston area in 1900 and 2008; and storm surge events that impacted the Florida Keys. These comparisons confirm that prelandfall wind speeds are an important factor for generating high-magnitude storm surges and may generally be as important as storm size.

Hurricane Danny followed a similar track as Lili, as both storms moved northwest from the central Gulf of Mexico and made landfall just west of Vermillion Bay, Louisiana. Danny’s 80-kt maximum sustained wind at landfall (National Hurricane Center 1985) also matched Lili’s landfall wind speed (Pasch et al. 2004). However, Danny’s peak surge was only 2.44 m (National Hurricane Center 1985), about 1.31 m lower than Lili’s peak surge of 3.75 m (Pasch et al. 2004).

How did Lili generate a storm surge more than 50% higher than Danny, when both storms made landfall with identical wind speeds? The physical profile of the coastal region, including bathymetry, proximity to the coastal shelf, and the shape and geometry of the coastline, does not likely explain the difference. These variables should have been nearly constant in these two storms, although changes in the coastline over time from coastal erosion, subsidence, and other issues related to the coastal morphodynamics in this region may have had a slight influence on surge heights.

Hurricane size does not explain this difference either, because Danny’s geographic size was comparable or larger than Lili’s, even though it generated the smaller storm surge. Hurricane Lili was a small hurricane: the radius of maximum wind was only 19 km (10 n mi) (Demuth et al. 2006). Unfortunately, published hurricane size data were not available for Hurricane Danny. To compensate for this lack of data, we utilized thermal infrared satellite imagery to measure the distance from the warmest hurricane eye pixel to the pixel with the coldest cloud-top temperature in this storm. This methodology had previously been used to estimate the size of Hurricane Lili. The distance from between Lili’s warmest eye pixel and coldest cloud-top pixel measured 29.1 km (15.7 n mi) (S. A. Hsu and A. Babin 2005, personal communication).

We measured these distances for both Danny and Lili in Louisiana State University’s Earth Scan Laboratory. Satellite images were provided by the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Large Array-Data Stewardship System (CLASS) program (NOAA CLASS 2013). We utilized Geostationary Operational Environmental Satellite-8 (GOES-8) and GOES-10 infrared satellite imagery to measure the size for Hurricane Lili. The temporal resolution was 12 images per hour and the pixel size was 4 km × 8 km. We obtained a distance of 45 km (24.3 n mi) between the eye and coldest cloud top at 18 h before landfall and 39 km (21 n mi) at 16.25 h before landfall, which was approximately the same time that Hsu and Babin (S. A. Hsu and A. Babin 2005, personal communication) made their measurement. The distance we measured was slightly larger than the distance provided by Hsu and Babin (S. A. Hsu and A. Babin 2005, personal communication). No eye was visible on thermal infrared imagery for Lili at the time of landfall. We utilized GOES-6 infrared satellite imagery, with 30-min temporal resolution and pixel size of 4 km × 8 km, to measure the size of Hurricane Danny. No eye was clearly visible 18 h before landfall; however, a discernible eye was visible at the time of landfall and a distance of 56.5 km (30.5 n mi) was measured. Although these results make it difficult to make an exact size comparison between Danny and Lili, because they were
measured at different time intervals before landfall, they do suggest that Danny was comparable in size or larger than Lili, which rules out the possibility that size differences contributed to the differences in surge magnitudes.

As various parameters, such as storm size, bathymetry, and landfall wind speeds, are eliminated as the explanation in the difference of these two surge magnitudes, the difference in prelandfall wind speeds emerges as the most likely explanation. Although the maximum sustained wind speeds of these storms were identical at landfall, Lili was a powerful category 4 hurricane with winds of 232 km h\(^{-1}\) (125 kt) while centered over the north-central Gulf of Mexico (Pasch et al. 2004), while Danny strengthened as it approached the coast, reaching its peak intensity around the time of landfall (National Hurricane Center 1985).

A comparison between Hurricane Ike and the 1900 Galveston hurricane also supports the importance of prelandfall winds for generating high-magnitude storm surges. Both of these storms made landfall on Galveston Island and generated destructive surges. Hurricane Ike was the larger of the two storms, with an Rmax size of 93 km (50 n mi) at 18h before landfall and 56 km (30 n mi) at landfall (Demuth et al. 2006). In contrast, the 1900 Galveston hurricane was a relatively small storm, with an Rmax size of 26 km (14 n mi) (Ho et al. 1975; Simpson and Riehl 1981; Landsea et al. 2003). Although the 1900 Galveston hurricane was a smaller storm, it generated a higher storm surge, which reached a height of 6.1 m (Garriott 1900). This was slightly higher than Hurricane Ike’s peak surge, which reached 5.33 m (Berg 2010). Prelandfall winds emerge as the most likely reason that the 1900 Galveston hurricane generated a higher surge. The storm was a powerful category 4 hurricane with a maximum sustained wind speed of 232 km h\(^{-1}\) (125 kt) at 18 h before landfall, which enabled the storm to produce large swells and thunderous surf that were observed on Galveston Island well before the strong winds arrived (Garriott 1900; Larson 1999; Keim and Muller 2009). Hurricane Ike, however, was a category 2 hurricane with a maximum sustained wind speed of 176 km h\(^{-1}\) (95 kt) at 18 h before landfall and oscillated between category 2 and category 3 intensity as it approached the coast. The bathymetry related to both storms should have been relatively constant.

The storm surge history of the Florida Keys further supports the notion that prelandfall winds are important for generating high surges. In particular, the 1935 Labor Day hurricane provides clear evidence of the potential for compact, intense hurricanes to generate catastrophic surges. This cyclone generated a 5.49-m surge in the Florida Keys (Knowles 2009, Chart File 3-16-10,409), which is the highest modern-day storm surge in this region (Needham and Keim 2012). Interestingly, this storm was also the smallest tropical cyclone to strike this region. The Rmax size of this storm was only 11 km (6 n mi) (Ho et al. 1975), which made it one of the smallest tropical cyclones to ever strike the United States. Intense prelandfall winds likely explain how this small storm was able to generate such a high storm surge. This storm was a category 4 hurricane 18 h before landfall and generally strengthened as it approached the Keys, reaching category 5 strength approximately 6 h before landfall (Elsner and Jagger 2013).

While these comparative storm surge events provide substantial evidence that prelandfall winds are important for storm surge generation, they also demonstrate that we must be careful about categorizing hurricanes by their landfall intensities when referring to coastal flooding. For example, both Hurricanes Danny and Lili
made landfall as category 1 hurricanes in south Louisiana, but Lili was a category 4 hurricane before landfall and produced a storm surge height 50% higher than Danny. Suggesting that both of these storm surges were generated by category 1 hurricanes may mislead readers into believing that little relationship exists between maximum wind velocity and storm surge heights.

Although Hurricane Ike is usually referred to as a category 2 hurricane that generated a massive storm surge, spline-interpolated wind and position data indicate that the storm actually crossed the category 3 threshold multiple times as it approached the Texas coast (Elsner and Jagger 2013). Meanwhile, Hurricane Charley is often referred to as a category 4 hurricane that generated a small surge. However, 9 h before landfall the storm was only a category 2 hurricane and at 18 h before landfall, when the strongest relationship exists between surge heights and maximum sustained winds, Charley was centered in the Caribbean Sea, south of Cuba, and was therefore displacing only a minimal amount of water in the Gulf of Mexico. While differences in storm size and bathymetry surely enabled Ike to generate a larger surge than Charley, the importance of these parameters is likely overemphasized when referring to Ike as a category 2 hurricane and Charley as a category 4 hurricane. A comparison of these storms further supports the importance of prelandfall winds, as Ike was actually a more intense tropical cyclone than Charley at 9 h before landfall (Elsner and Jagger 2013) and Charley was not even centered over the Gulf of Mexico 18 h before landfall.

Some may argue that Charley generated a relatively small surge because the bathymetry off the coast of southwest Florida is too deep to enable hurricanes to produce high storm surges in this region. However, other coastal flooding events in this region prove that relatively high storm surge levels can be reached in southwest Florida. In 1992, Hurricane Andrew generated a 4-m storm tide at North Highland Beach (Risi et al. 1995; Tedesco et al. 1995; Smith et al. 2009), and Hurricane Wilma in 2005 generated a storm surge of at least 4.72 m between Lostman’s ranger station and Big Sable Creek, in extreme southwest Florida (Barnes 2007; Smith et al. 2009). Both of these sites are located within 140 km (76 n mi) of the peak surge location for Hurricane Charley. Also, storm surge modelers must recognize the potential for relatively high storm surges in this region because the National Hurricane Center forecasted Hurricane Charley’s peak storm surge to reach between 3.05 and 4.57 m (National Hurricane Center 2004). If deep bathymetry off the coast of southwest Florida eliminated the potential for relatively high storm surges in this region, surge models could not have predicted a surge of this magnitude for Hurricane Charley. These various factors indicate that, while bathymetry might have played a role in Charley’s storm surge magnitude, the relatively low surge level was most likely due to a combination of small storm size and modest prelandfall wind speeds, which were much less intense than the wind speeds at landfall.

Comparisons between Hurricanes Katrina and Camille provide a final but important example of hurricane classifications that may unintentionally mislead people, when related to coastal flooding. Katrina is often referred to as a category 3 hurricane, based on its landfall intensity. When compared with Hurricane Camille, which made landfall as a category 5 hurricane in the same region yet generated a lower storm surge, one may conclude that tropical cyclone wind speeds do not correlate well with surge heights. A difference in storm size emerges as the best
explanation for these storm surge heights once maximum sustained winds are eliminated as a factor, because the bathymetry and coastal geomorphology near these two surge events should have been relatively constant. While storm size likely was an important factor that enabled Katrina to generate a high storm surge, the importance of size may be overestimated if Katrina’s intense prelandfall winds are overlooked. Katrina’s maximum sustained wind speed of 274 km h\(^{-1}\) (148 kt) (Elsner and Jagger 2013) at 18 h before landfall was ranked second for all storms in this study, exceeded only by Hurricane Camille. In fact, the prelandfall wind speeds of these two storms were comparable, as Camille’s sustained winds only exceeded Katrina’s by 20 km h\(^{-1}\) (11 kt) at 18 h before landfall (Elsner and Jagger 2013).

We do not suggest that prelandfall wind speed is the predominant variable that influences storm surge height, nor do we imply that other physical parameters have little influence in generating storm surges. We simply suggest that the scientific community should be careful about characterizing past storms and make sure that prelandfall wind speed is considered for cases in which tropical cyclones strengthened or weakened when approaching the coastline.

Comparisons of historic storms, taken in conjunction with the statistical analysis of this study, suggest that the larger of two tropical cyclones with comparable prelandfall winds will generate a larger storm surge, while the tropical cyclone with stronger prelandfall winds will likely generate the larger storm surge if two storms have comparable sizes and relatively similar bathymetry.

These results should improve surge prediction as modelers give more weight to prelandfall winds in storm surge forecasts. This will also improve surge prediction because prelandfall wind forecasts should be more accurate, on average, than landfall forecasts. As a tropical cyclone approaches the coast, complex factors such as the effect of dry-air entrainment and sea surface temperature changes become more prominent, making wind speed forecasts more difficult. However, wind speed forecasts are generally more accurate for tropical cyclones over open water.

Therefore, using prelandfall winds as a predictor of surge heights should provide more accurate forecasts, because tropical cyclones are generally positioned well offshore 18 h before landfall. The average distance between the center of circulation at landfall and at 18 h before landfall was 369 km (199 n mi) for wind–surge events used in this analysis. The maximum distance was 739 km (399 n mi), produced by an unnamed cyclone in late September 1924 that generated a peak surge height at Cedar Key, Florida. The minimum distance was approximately 67 km (36 n mi), produced by an unnamed tropical cyclone in late September 1929 that generated a peak surge observation at Key Largo, Florida. Dividing these distances by 18 h provides an average forward speed of 20.6 km h\(^{-1}\) (11.1 kt), a maximum forward speed of 40.9 km h\(^{-1}\) (22.1 kt), and a minimum forward speed of 5.9 km h\(^{-1}\) (3.2 kt).

6. Summary and conclusions

This paper investigated relationships between storm surge heights and tropical cyclone winds at and before landfall. Elsner and Jagger (Elsner and Jagger 2013) provided a unique tropical cyclone dataset, which contained hourly tropical
cyclone position and wind speed data. Maximum storm surge levels for 189 Gulf of Mexico surge events from 1880 to 2011 were provided by SURGEDAT (Needham and Keim 2012). A landfall/surge classification was developed to determine the time of landfall and 3-h increments preceding landfall.

LOESS regression modeling indicates that storm surge magnitudes correlate better with prelandfall wind speeds than wind speeds at landfall, with wind speeds 18 h before landfall producing the best correlation. These results were duplicated on tests of 63 wind–surge events from 1960 to 2011. Wind speeds 18 h before landfall also produced the best correlation and provided even better correlation than the longer dataset.

We validated these results by comparing some historical wind–surge events that occurred near each other spatially. Lili’s strong prelandfall winds likely enabled the storm to generate a surge more than 50% higher than Hurricane Danny, as the maximum sustained winds at landfall in these storms was equal, Danny was comparable in size or slightly larger, and bathymetry in the region of these storms was relatively constant. The intense prelandfall winds of the 1900 Galveston hurricane likely enabled this storm to generate a higher storm surge than Hurricane Ike, as both storms made landfall on Galveston Island, and the more intense but smaller Galveston hurricane generated a higher-magnitude surge. Also, the 1935 Labor Day hurricane was one of the smallest hurricanes to strike the United States, but it generated the highest-magnitude surge event in the history of the Florida Keys. Prelandfall winds likely influenced this surge height, as the storm approached the Keys as an intense tropical cyclone.

Although it appears that prelandfall winds are important for generating high-magnitude storm surges, storm size is important for generating extensive surge events, which may actually inundate more area than a surge with a higher peak magnitude. Hurricane Ike’s large size enabled this storm to inundate areas in southeast Louisiana that were not likely flooded from the 1900 Galveston hurricane. This observation provides an important caveat to this study: our results have only tested the relationship between prelandfall winds and peak surge levels, but we have not considered the extent of storm surge or area of inundation. Emergency management personnel and other coastal stakeholders should be aware that tropical cyclones with large wind fields have the capacity to inundate long stretches of coastline, which may flood areas far from the region of landfall.

This study also found that the relationship between maximum winds and surge heights is more nonlinear than previously expected. A test run on the 63 wind–surge events since 1960 showed the wind–surge relationship correlates best when wind values from 18 h before landfall are raised to an exponential power of 2.2, producing an $R^2$ value of 0.6948. However, existing literature on this relationship suggested the optimal exponential power should be less than 2 (Jordan and Clayson 2008). The relationship between maximum sustained winds and peak surge levels is surprisingly nonlinear, as these values indicate that doubling the maximum sustained winds of tropical cyclones increases surge potential by a factor of 4.59. As tropical cyclones may strengthen in a warmer climate (Emanuel 2005; Anthes et al. 2006; Karl et al. 2009), this finding may have dire consequences for coastal regions, because even modest increases in tropical cyclone wind speeds would produce relatively large increases in surge height. Sea level rise, which is
accelerating at many locations (Zervas 2001), may also exacerbate storm surge inundations in the future.

These results will likely improve storm surge modeling as scientists give more weight to prelandfall winds in surge forecasts. Although such models may utilize prelandfall wind speeds 18 h before landfall as an important indicator of storm surge potential, the forecasts may actually be issued at least several days before landfall. The scientific literature on the physical processes that generate storm surge contains little information on the importance of prelandfall winds, so these results have not likely been incorporated into forecasting algorithms. These findings may help surge forecasts improve considerably, as prelandfall tropical cyclone wind forecasts tend to be more accurate than landfall wind forecasts.

These results may have implications for disaster science/emergency management professionals, especially for hurricanes that are rapidly strengthening or weakening just before landfall. Local authorities may want to prepare more for a wind event in storms that rapidly strengthen just prior to landfall, a surge event in storms that were once intense but rapidly weaken before landfall, and both hazards for storms that hold consistent intensity as they approach the coast.

The benefits of improved evacuation decisions are substantial, as evacuations are costly. It is estimated that the cost to evacuate 1 mile of coastline is approximately 1 million U.S. dollars (Adams and Berri 1999; Whitehead 2003; Wolshon et al. 2005; Regnier 2008). The cumulative cost of false hurricane evacuations is staggering; such false alarms cost an average of more than 1 billion U.S. dollars per year from 2000 to 2006 (Regnier 2008). Also, local authorities may lose credibility after false evacuation orders, making the public more likely to turn to other information sources in future storms (Dow and Cutter 1998).

Although this paper focused on the influence of maximum sustained wind speeds for storm surge generation in tropical cyclones, future research could focus on the influence of multiple parameters for generating surge, including tropical cyclone size, forward speed, and prelandfall wind velocity, as well as nonstorm variables, such as bathymetry and coastal shape. Emerging fields in computer science, such as data mining, machine learning, and geoinformatics, may be useful for such analyses, because multiple variables interact simultaneously to generate storm surge as a tropical cyclone approaches the coastline. Such methods could potentially unravel complex relationships between variables, such as the influence of tropical cyclone size for generating storm surge over shallow bathymetry or the expected difference in surge heights from two storms with identical size and bathymetry but different prelandfall wind speeds. Such data-driven research may offer new insights not provided by hydrodynamical models.

Future studies could also investigate the role of prelandfall winds in other ocean basins vulnerable to tropical cyclone–generated storm surges. Such efforts may reveal how variations in coastal shape and bathymetry may affect the correlation between prelandfall winds and storm surge magnitude. The potential for such projects exist in every ocean basin vulnerable to storm surge, as the SURGEDAT database develops internationally.
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References


